Received: 17 September 2020 | Revised: 7 May 2021 | Accepted: 17 August 2021

DOI: 10.1002/dys.1700

RESEARCH ARTICLE

WILEY

The extraction of orthographic and phonological structure of printed words in adults with dyslexia

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The current study investigated the extraction of orthographic and phonological structure of written words in adults with dyslexia. In adults without learning difficulties, Chetail and Content showed that orthographic structure, as determined by the number of vowel letter clusters, influences visual word length estimation. The authors also found a phonological effect determined by the number of syllables of words. In the present study, 22 French-speaking students diagnosed with dyslexia in childhood and 22 students without learning disabilities were compared. All participants performed the task of estimating word length. The pattern of results obtained by Chetail and Content was replicated: length estimates were biased by both the number of syllables and the number of vowel letter clusters. The study showed a significant interaction between phonological bias and group. The phonological effect was less important in students with dyslexia, suggesting reduced sensitivity to phonological parsing in reading. In contrast, the orthographic effect did not differ significantly between groups, suggesting that the sensitivity to the orthographic structure of written words is preserved in students with dyslexia despite their low-quality orthographic representations. We conclude that there is no systematic association between

All the materials, raw data, and scripts for the analyses are available on the Open Science Framework: https://osf.io/bgz2h/.

sensitivity to the structure of representations and quality of their content.

KEYWORDS
consonants and vowels, dyslexia, orthographic structure, phonological structure, word identification

1 | INTRODUCTION

Difficulties in written word identification persist in adults with dyslexia and affect their reading skills. However, efficient recognition of individual words is one of the most essential components of reading, because it precedes and directly conditions the comprehension of sentences and texts. The process of visual word recognition is complex, involving the retrieval of orthographic, phonological, and semantic information from the visual input. It is often assumed that at first, information spreads from print to letter feature representations to letter representations, which, in turn, activate word representations (e.g., McClelland & Rumelhart, 1981). However, psycholinguistic studies carried out with skilled readers in recent decades have provided evidence for a more complex hierarchy of representations, with the existence of intermediate units between the letter and word levels. Among the putative sublexical units activated during word recognition, onset and rimes, syllables or even morphemes have been put forward (Balota, Yap, & Cortese, 2006). In addition, the orthographic structure of words seems to be an important parsing clue in word processing (Chetail & Content, 2012; Prinzmetal, Hoffman, & Vest, 1991; Seidenberg, 1987). The aim of the present study was to investigate to what extent the orthographic and phonological structure of written words are automatically extracted by students with dyslexia and, thus, contribute to a better understanding of reading processes and mental representations in reading impaired adults.

Developmental dyslexia is a specific learning disorder that affects the ability to acquire accuracy and/or fluency in reading and that is not consistent with the person's chronological age, educational opportunities or intellectual abilities (American Psychiatric Association, 2013). It takes the form of persistent difficulties in quickly and accurately identifying familiar written words, decoding unfamiliar sequences of letters and producing the correct spelling of words. A substantial body of literature indicates the persistence of these difficulties in adulthood (Bruck, 1990; Callens, Tops, & Brysbaert, 2012; Hatcher, Snowling, & Griffiths, 2002; Martin et al., 2010; Swanson & Hsieh, 2009). Furthermore, adults with childhood diagnoses of dyslexia continue to exhibit significant disabilities in phonological processing (Bruck, 1992). Phonological processing deficits are considered by many authors to be the core deficit in developmental dyslexia (Ramus, 2003; Snowling, Nation, Gallagher, & Frith, 1997; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Studies with adolescents and adults with developmental dyslexia suggest that they have poorly specified phonological representations (Elbro & Jensen, 2005; Elbro, Nielsen, & Petersen, 1994), impaired sub-lexical phonological representations (Szenkovits & Ramus, 2005) or deficient access to phonological representations (Ramus & Szenkovits, 2008). In addition to reading and phonological processing deficits, adults with dyslexia perform poorly in spelling (Lefly & Pennington, 1991). Studies also indicate problems in establishing fully specified novel orthographic representations (Biname, Danzio, & Poncelet, 2015; Poncelet, Schyns, & Majerus, 2003), when clear orthographic representations are necessary for efficient word-level reading and accurate spelling (Apel, 2009). Electrophysiological and neuroimaging data support the hypothesis of deficient orthographic and phonological representations and/or deficits in linking these representations together (Araújo, Faísca, Bramão, Reis, & Petersson, 2015; Cao, Bitan, Chou, Burman, & Booth, 2006; Hasko, Bruder, Bartling, & Schulte-Korne, 2012; Meyler & Breznitz, 2005; Savill & Thierry, 2011). To what extent adults with dyslexia rely on the phonological and orthographic structure of word representations stored in long-term memory remains an open question. Before describing the few studies that focused on phonological and orthographic parsing in persons with dyslexia, we first discuss the impact of phonological and orthographic units on written word processing in skilled readers.

1.1 | Phonological and orthographic parsing in skilled readers

Many studies have demonstrated the importance of phonological structure determined by syllable units in visual word recognition. For example, the effect of the number of syllables (Ferrand & New, 2003; Stenneken, Conrad, & Jacobs, 2007) and the effect of first-syllable frequency (Alvarez, Carreiras, & de Vega, 2000; Carreiras, Alvarez, & de Vega, 1993; Conrad, Grainger, & Jacobs, 2007) both suggest that syllabic parsing takes place during visual word recognition. In experiments manipulating the number of syllables in words (while controlling for word frequency and length), a larger number of syllables is associated with longer reaction times in naming or lexical decision tasks (e.g., Ferrand & New, 2003). Furthermore, the presence of a high-frequency first syllable leads to slower word recognition, which is thought to result from increased competition between candidates sharing the initial syllable with the target word (e.g., Carreiras et al., 1993). These results suggest that syllables are functional reading units, automatically activated during visual word processing.

Other studies have shown that readers are sensitive to orthographic regularities and suggest that sublexical parsing into perceptual units is not driven by phonological information but by orthographic knowledge. Letter co-occurences (identity and position of letters, sometimes referred to as "orthographic redundancy," see Chetail, 2017) are thought to be especially important, and, in particular, letter cluster frequencies (Seidenberg, 1987). Seidenberg (1987) noticed that bigrams forming the boundary between two syllables are usually less frequent than intrasyllabic bigrams (thus creating a "bigram trough," e.g., in ANVIL, the frequency of the bigram NV around the syllable boundary is lower than the frequency of the intrasyllabic bigrams AN and VI). Readers are sensitive to such transitional probabilities between letters, and according to Seidenberg's bigram trough hypothesis, it is this kind of orthographic information that drives word parsing (i.e., ANVIL would be parsed and processed as a two-unit input, not due to its syllabic structure but because of the bigram trough between N and V).

1.2 | Two complementary views

These two points of view (syllabic vs. orthographic units) are not necessarily contradictory. Using the illusory conjunction paradigm (Prinzmetal, Treiman, & Rho, 1986), Doignon-Camus and Zagar (2005, 2006) showed that reading units are defined by two information sources: phonological syllables and orthographic redundancy. In this task, participants have to detect a target letter in bisyllabic words the letters of which are in two different colours (e.g., T in MATin or MAtin; upper and lower case representing two different colours), and have to report its colour. Stimuli are devised, so that colours respect or violate the syllable and the orthographic boundaries. Orthographic and phonological boundaries either coincide in the congruent condition (e.g., MA/*TIN, for which the bigram AT straddling the syllable boundary is of low frequency; the slash marks the syllable boundary and the asterisk marks the orthographic boundary) or do not coincide in the conflicting condition (e.g., RU/B*AN). Among the possible errors, illusory conjunctions (associating the wrong colour to the target letter) are particularly interesting, because they reflect perceptual grouping mechanisms. Indeed, the authors found a bias towards syllable boundaries in the participants' responses (e.g., in MATin, erroneously reporting the letter T as being of the same colour as the letters "in", in line with the syllabic structure), but this syllable effect was significantly smaller when syllable boundaries did not coincide with bigram boundaries, indicating an influence of both structures in print processing. These results are particularly relevant, because, similarly to the task used in the present study, the illusory conjunction paradigm does not require lexical access nor explicit processing of perceptual units. It, thus, makes it possible to probe the automatic activation of orthographic and phonological structure without driving participants' attention towards it.

Syllabic and orthographic effects actually seem to reflect two independent processes. Conrad, Carreiras, Tamm, and Jacobs (2009), for example, found that orthographic letter clusters (bigrams) and syllabic units affect visual word recognition at different processing levels: early prelexical processing vs. activation of lexical candidates respectively. In their experiments, the authors found an inhibitory syllable frequency effect, which is traditionally interpreted as resulting from the activation of lexical candidates competing for identification. In contrast, they observed a facilitatory effect of initial bigram frequency, which rather seems to reflect early prelexical processing, in agreement with the view that bigram frequency might facilitate prelexical orthographic processing.

1.3 | The CV pattern hypothesis

More recently, Chetail and Content (2012, 2013, 2014) put forward a new hypothesis regarding the issue of reading units and perceptual parsing. This led them to assess the respective contribution of phonological and orthographic information in written word recognition. According to their hypothesis, the arrangement of consonant and vowel letters (CV pattern) in the letter string provides powerful parsing cues. Each group of contiguous vowel letters constitutes an orthographic unit core element, to which adjacent consonants aggregate. It is, therefore, possible to segment a word into consonant–vowel clusters. Most often, CV parsing corresponds to spoken syllable segmentation. To distinguish the impact of phonological syllabic structure and orthographic CV structure, Chetail and Content used items that differed in terms of number of syllables and number of consonant–vowel clusters, such as words with a hiatus pattern (see Table 1). These words are particularly interesting, because there is a mismatch between orthographic and phonological structures. Indeed, due to the sequence of two full vowels defining a single orthographic vowel cluster but determining two syllabic nuclei, hiatus words have more syllables than orthographic units.

The CV pattern hypothesis has been tested in several experiments in different languages (Chetail, Scaltritti, & Content, 2014; Chetail, Treiman, & Content, 2016), using different tasks: syllable-counting (Chetail & Content, 2012, 2013), same-different matching (Chetail, Drabs, & Content, 2014), naming and lexical decision (Chetail & Content, 2012) and length estimation (Chetail & Content, 2014). In all these experiments, the number of vowel cluster units was found to have an impact on word processing. For example, in the syllabic counting task, adults underestimated the number of syllables in hiatus words (e.g., the tendency to decide that REUNION has two syllables instead of three). In the same-different task, participants were instructed to decide as rapidly and accurately as possible whether a target letter string (e.g., *poirver*) was identical to the previously presented referent (e.g., *POIVRER*). Mismatches were detected more rapidly when the CV structure of the referent and target differed than when they did not (e.g., *povirer—POIVRER* vs. *piovrer—POIVRER*). This orthographic effect was also present in the word length estimation task (Chetail & Content, 2014), in which participants had to estimate the physical length of written words

TABLE 1 Examples of hiatus and control words in English and in French

English examples						
Word structure	**Control word**			**Hiatus word**		
Item	EVASION			REUNION		
CV pattern	V	CV	CVVC	CVV		CVVC
Orthographic parsing	E	VA	SION	REU		NION
Syllabic structure	/ɪ/	/veɪ/	ʒən/	/ri/	/ju/	/njən/
French examples						
Word structure	**Control word**			**Hiatus word**		
Item	DÉLIVRER			CRÉATION		
CV pattern	CV	CV	CCVC	CCVV		CVVC
Orthographic parsing	DÉ	LI	VRER	CRÉA		TION
Syllabic structure	/de/	/li/	/vʀe/	/kʀe/	/a/	/sjɔ̃ /

Abbreviations: C, consonant; V, vowel.

briefly presented (50 or 100 ms) on a computer screen by drawing a line with the mouse. This task, therefore, does not require word identification or access to phonology. The results indicated that length estimates were biased by the number of vowel letter clusters even when the words had the same number of letters (words comprising fewer orthographic units were estimated to be shorter than words comprising more units). Such results suggest that the CV pattern affects processing at an early prelexical processing stage. This was confirmed in a magnetoencephalography study showing that the CV pattern effect was associated with a significant difference in evoked neuromagnetic fields extending from 129 to 239 ms after the stimulation and associated with the visual word form area (left fusiform regions) (Chetail, Ranzini, De Tiège, Wens, & Content, 2018).

In the length estimation task, Chetail and Content (2014) also found a significant effect of the phonological syllabic structure when the words were presented for 100 ms. Participants estimated trisyllabic words as being longer than bisyllabic words when the effect of number of letters, of number of vowel cluster units and of physical length was partialled out. These results prompted the authors to consider that visual word recognition takes both syllabic and orthographic structure into account (Chetail, 2015; Chetail, Drabs, & Content, 2014).

1.4 | Phonological and orthographic parsing in dyslexia

Some studies focused on phonological and orthographic parsing in poor readers. Poor readers experience difficulties in the use of orthographic structure (Massaro & Taylor, 1980) and show weaker effects of orthographic redundancy and syllable structure than skilled readers (Butler, Jared, & Hains, 1984). Similarly, the results obtained by Prinzmetal et al. (1991) indicated a greater effect of orthographic information in good readers than in poor readers, suggesting that automatic sensitivity to reading units is correlated with reading ability.

In children with developmental dyslexia, Doignon-Camus, Seigneuric, Perrier, Sisti, and Zagar (2013) used the illusory conjunction paradigm to investigate the sensitivity to orthographic redundancy and syllabic structure in French. They found that typically developing children were sensitive to both phonological syllables and orthographic redundancy, whereas in children with dyslexia, reading units were defined only by orthographic redundancy. The authors concluded that access to phonological syllables from letters was impaired in children with dyslexia, while their ability to exploit letter co-occurrence frequency was preserved.

However, contradictory results have been reported. Maïonchi-Pino, Magnan, and Écalle (2010) asked children to decide as quickly and as accurately as possible whether a target occurred at the beginning of a test word (e.g., *CA* in *CAROTTE*). They observed that children with dyslexia were sensitive to syllabic structure and initial syllable frequency. Furthermore, in adults with dyslexia, Pitchford, Ledgeway, and Masterson (2009) observed reduced sensitivity to positional letter frequency and argued that the deficit could stem from difficulties in extracting statistical regularities from orthographic input. In an ERP study using an implicit reading task, Araújo et al. (2015) found deviations in the early activation related to sublexical orthographic analysis in adults with dyslexia. The orthographic regularity effect (pseudowords–nonwords contrast) was not observed in this group, indicating an impaired sensitivity to orthographic structure. Nevertheless, while these results highlight impaired sub-lexical orthographic analysis, other studies suggest partly preserved or compensated orthographic skills in adolescents and adults with dyslexia (Miller-Shaul, 2005). Siegel, Share, and Geva (1995) used an orthographic awareness task with a large sample of individuals with dyslexia, including adolescents (grade 8). Participants with dyslexia had significantly higher scores than typically achieving readers matched in reading level in recognizing bigrams that occurs or not in English words. Siegel et al. argued that individuals with poor phonological skills may be more likely to use visually mediated strategies in reading.

In conclusion, while numerous studies have shown that phonological and orthographic processes are affected in dyslexia, very few studies specifically focused on phonological and orthographic parsing. However, focusing on parsing is necessary to understand to what extent the hierarchy of reading units is activated during word processing. In addition, these studies have yielded inconsistent results, highlighting that more data are needed. To our knowledge, the only study that has investigated both orthographic and phonological syllable structure sensitivity in print processing in this population has been carried out by Doignon-Camus et al. (2013) in children. As such, these results cannot be readily generalized to adults. Furthermore, most researchers agree on the central and causal role of phonology in dyslexia, but they have different views about the nature of the phonological deficit (Ramus, 2003; Ramus & Szenkovits, 2008). Phonological processes are particularly complex to assess, because most paradigms measure the outcome of the dynamic interaction between many levels of representation and processing. In this context, it seems particularly relevant to explore specifically the processes related to the earliest stages of visual word identification, and the length estimation task (Chetail & Content, 2014) seems well-suited to that aim.

2 | THE PRESENT STUDY

The aim of the present study was to reach a better understanding of the sensitivity of adults with dyslexia to orthographic and phonological structure. To do so, we used the length estimation task, in which participants have to estimate the physical length of words presented visually. One of the key advantages of this task is that it provides an indirect measure of structural effects, without directing participants' attention towards word structure or word constituents. Furthermore, as the task does not require word identification or access to phonological representation to be correctly performed, it may isolate processes related to the earliest stages of visual word identification. As explained above, hiatus words for which there is a mismatch between phonological and orthographic structure can be used to examine the impact of each type of structure.

For typically developing readers, we expected to replicate previous results, namely an orthographic effect (hiatus words estimated to be shorter than control words when length is strictly controlled for) and a phonological effect (trisyllabic words considered to be longer than bisyllabic words after the effect of other variables is partialled out). In adults with dyslexia, based on the phonological core theory of dyslexia (Ramus, 2003; Snowling et al., 1997; Vellutino et al., 2004), we expected a smaller or even no phonological effect. Regarding the orthographic effect, if adults with dyslexia suffer from a lack of sensitivity to orthographic structure (Pitchford et al., 2009), a smaller or even no effect should be observed.

3 | METHOD

3.1 | Participants

Twenty-two French-speaking higher-education students diagnosed with developmental dyslexia in childhood were recruited. They had all applied for a global assessment in order to obtain advice or special support measures in higher education. The assessment was conducted by a certified professional at the Consultations Psychologiques Spécialisées of the Université catholique de Louvain (Belgium) and confirmed persistent difficulties in reading and spelling. These participants were all contacted after their assessment and asked if they were willing to participate in the present study. Twenty-nine French-speaking control students who reported no previous history of reading and spelling impairment also took part in the experiment following a call for participation posted on an internet platform of the university.

All the participants reported having normal or corrected-to-normal vision and normal hearing. They had no history of neurological or sensory disorders and no comorbid diagnosis of attention disorders. They were all native French speakers and were studying for a bachelor's degree. The participants were recruited from different fields of study. They received a financial compensation for their participation.

The experiment described in this paper was part of a larger study in which a diagnostic battery was administered to all the participants. This diagnostic battery was composed of several standardized tests, including tests of reading (accuracy, speed and comprehension) and spelling (accuracy and speed): a pseudoword and word reading task (Phonolec; Plaza, Robert-Jahier, Gatignol, & Oudry, 2008), a narrative (Evalad; Pech-Georgel & George, 2011) and meaningless (Alouette; Lefavrais, 1967, 2005) text reading task, a word and pseudoword writing task (Phonolec; Plaza et al., 2008), and a text writing task (Evalad; Pech-Georgel & George, 2011). The participants were individually tested in two sessions of approximately one and half hours each.

Some participants in the control group—that is, without reading and spelling complaints—nevertheless, exhibited deficits in norm-referenced tests evaluating reading and spelling abilities and were excluded from the sample ($n = 7$). We chose a cutoff score at 1.5 SD below the mean of the control group. As a control subject may occasionally show abnormal performance in one task, the students eliminated were those who obtained at least two scores more than −1.5 SD lower than the entire control group in reading or spelling tests. An a posteriori check was conducted to ensure that the two groups were matched overall in terms of gender, age, handedness, socio-economic level and academic level. More information on the participants is available in Table 2.

The scores of the two groups on the Alouette reading test (Lefavrais, 1967, 2005) are presented in Table 3. This test is a sensitive and specific screening tool for French adults with dyslexia (Cavalli et al., 2018). It allows us to measure the efficiency of the decoding of each group taking into account accuracy and speed (a higher score corresponds to a better performance). We found a significant difference between students with dyslexia and typically developing readers in reading efficiency, $U = 7.50$, $p < .001$ (given the non-normal distribution of scores, the data were analysed with the nonparametric Mann–Whitney U test). The scores on the regular and irregular low-frequency word writing task are also provided in Table 3. This task is particularly interesting in the context of this experiment, because it is deemed to give an indication of the quality of orthographic representations of participants. The performance of typically developing readers was significantly higher than that of students with dyslexia ($U = 91.00$, $p < .001$, for regular word writing, and $U = 30.50$, $p < .001$ for irregular word writing). To test the phonological decoding skills, a pseudoword reading task (Phonolec; Plaza et al., 2008) was used. Students with dyslexia were significantly slower for both short and long pseudowords ($p < .001$). They were also less accurate, and the difference between groups was significant for short pseudowords, $U = 132.50$, $p = .008$, but not for long pseudowords, $U = 177.50$, $p = .125$. Finally, several tasks requiring the storage and the retrieval of phonological representations are presented in Table 3. These tasks assess phonological awareness (phoneme deletion, Phonolec; Plaza et al., 2008), short-term verbal memory (digit span, WAIS IV; Wechsler, 2011) and rapid automatized naming (RAN) (objects and digits, DRA adults; Gatignol, Plaza, & Robert-Jahier, 2007). The adults with dyslexia were significantly slower than the typically developing readers in phonological awareness and RAN tasks ($p \leq .002$). Moreover, they had a lower performance in the digit span task than the typically developing readers ($U = 124.00$, $p = .005$).

TABLE 2 Characteristics of participants (students with dyslexia and typically developing readers). Means are given as well as standard deviations in brackets when relevant

	Typically developing readers ($n = 22$)	**Students with dyslexia ($n = 22$)**
Gender (F: female/M: male)	15 F/7 M	15 F/7 M
Age	21.6 (2.6)	20.8 (1.0)
Laterality (R: right-/L: left-handed)	21 R/1 L	20 R/2 L
Socio-economic level	4.27 (0.88)	4.50 (0.67)
Academic level (first, second or third year of bachelor's program)	First year: 9 Second year: 10 Third year: 3	First year: 11 Second year: 9 Third year: 2

Note: The socio-economic level is the highest level of education of the parents (1: elementary school; 5: university).

TABLE 3 Means (and standard deviations) of scores in text reading, low-frequency word writing, pseudoword reading, phonological awareness, short-term verbal memory and rapid automatized naming and Mann–Withney *U* tests

	Typically developing readers ($n = 22$)	Students with dyslexia ($n = 22$)	*U* test
Text reading: reading efficiency	583.84 (86.02)	390.53 (55.08)	$U = 7.50$ $p < .001$
Low-frequency regular word writing (max. 10)	8.09 (1.44)	6.23 (1.54)	$U = 91.00$ $p < .001$
Low-frequency irregular word writing (max. 10)	7.05 (1.59)	3.14 (1.67)	$U = 30.50$ $p < .001$
Short pseudoword reading: time (s)	15.18 (3.60)	23.89 (4.54)	$U = 27.00$ $p < .001$
Short pseudoword reading: precision (max. 20)	18.68 (1.17)	17.41 (1.47)	$U = 132.50$ $p = .008$
Long pseudoword reading: time (s)	25.27 (6.07)	37.95 (6.19)	$U = 33.00$ $p < .001$
Long pseudoword reading: precision (max. 20)	16.55 (2.20)	15.41 (2.42)	$U = 177.50$ $p = .125$
Phoneme deletion: time (s)	17.81 (4.03)	24.95 (6.91)	$U = 94.00$ $p = .001$
Phoneme deletion: precision (max. 15)	13.68 (1.67)	13.00 (1.38)	$U = 166.00$ $p = .067$
Digit span (max. 16)	10.68 (1.99)	8.95 (1.56)	$U = 124.00$ $p = .005$
RAN (objects): time (s)	26.22 (2.86)	31.16 (6.65)	$U = 111.00$ $p = .002$
RAN (digits): time (s)	16.43 (2.50)	19.86 (3.40)	$U = 101.00$ $p = .001$

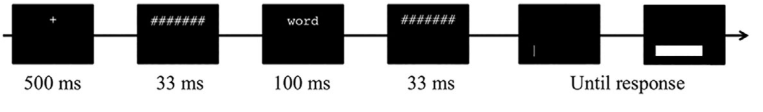

FIGURE 1 Example of a trial sequence

3.2 | Procedure

The procedure was the same as in Chetail and Content (2014). Presentation and response recording were programmed with the Psychtoolbox (Brainard, 1997). Items were displayed on an HP L1906 screen (1280 × 960 resolution). To ensure that hiatus and control words occupied the same spatial extent, stimuli were presented in lowercase fixed-width font. On each trial, a fixation cross appeared for 500 ms centred horizontally in the upper part of the screen (1/3 of the height from the top of the screen). The cross was followed by a 33 ms mask. The stimulus was then presented for 100 ms followed by the same mask. After that, the mouse cursor appeared in the lower part of the screen (1/3 of the height from the bottom of the screen). Its horizontal position varied randomly among six screen locations (extending from 3/12 to 8/12 of the width of the screen, measured from the left edge). Participants had to draw a line representing the physical length of the word. They used the mouse to lengthen or shorten the line and clicked to confirm their estimate (Figure 1). Participants performed nine practice trials with feedback (percentage accuracy of their estimate) before taking the 252 trials in random order. The task, divided into four blocks, lasted approximately 15 min. Participants could take a break between blocks.

3.3 | Stimuli

We used the same stimuli as in Chetail and Content (2014). A set of 168 French words was selected from Lexique (New, Pallier, Brysbaert, & Ferrand, 2004) according to the orthogonal combination of two factors, number of syllables and word type. Pairs of words were selected, matched for length in letters and phonemes, lexical frequency, and summed bigram frequency, with one word comprising a hiatus (e.g., création, /kʀe.a.sjɔ̃/) and the other not (e.g., délivrer, /de.li.vʀe/). Half of the words were bisyllabic and half trisyllabic. Eighty-four 3- or 9-letter-long fillers were added (for more details, see Chetail & Content, 2014).

4 | RESULTS

The raw data and script for the analyses are available on Open Science Framework (https://osf.io/bgz2h/). The analyses were conducted under R/RStudio environment (R Core Team, 2018; RStudio Team, 2016). Analyses of the difference between estimated word length and real word length (in pixels) were carried out on the students with dyslexia ($n = 22$) and the typically developing readers ($n = 22$).

Extreme values deviating from the real length by 90% or more were discarded from the analyses (0.34%). We fitted linear mixed-effect regression models including word type (hiatus and control) and number of syllables as fixed factors, and random intercepts for participants and items. As bi- and tri-syllabic words differed in number of letters and graphemes, these variables were added as covariates. Finally, as readers are generally exposed to proportional fonts and might, thus, rely on a memory representation incorporating letter size variations, we included a proportionality correction as an additional covariate (see Chetail & Content, 2014).

The mean estimates are presented in Table 4. Overall, for the group of typically developing readers as well as for the group of students with dyslexia, the estimated length was close to the real length for the control words (mean real length = 114 pixels; mean estimated length = 115 and 114 pixels, respectively). However, hiatus words were estimated as shorter than control words (orthographic effect), $\beta = -4.88$, $t = -8.44$, $p < .001$, and trisyllabic words were estimated as longer than bisyllabic words (phonological effect), $\beta = 5.37$, $t = 6.32$, $p < .001$. In addition, the number of letters, $\beta = 0.96$, $t = 50.53$, $p < .001$, and the proportionality correction, $\beta = -0.19$, $t = -6.02$, $p < .001$, were

TABLE 4 Real word length and estimated length (in pixels) as a function of word type for each group of participants

	All words		Bisyllabic words		Trisyllabic words	
	Estimated length	Real length	Estimated length	Real length	Estimated length	Real length
Typically developing readers						
Control words	118.5	114.5	98.1	96.8	139.0	132.1
Hiatus words	112.2	114.5	92.9	96.8	131.5	132.1
Difference	*6.3*		*5.2*		*7.4*	
Students with dyslexia						
Control words	116.5	114.5	97.9	96.8	135.1	132.1
Hiatus words	111.6	114.5	92.8	96.8	130.5	132.1
Difference	*4.9*		*5.1*		*4.6*	

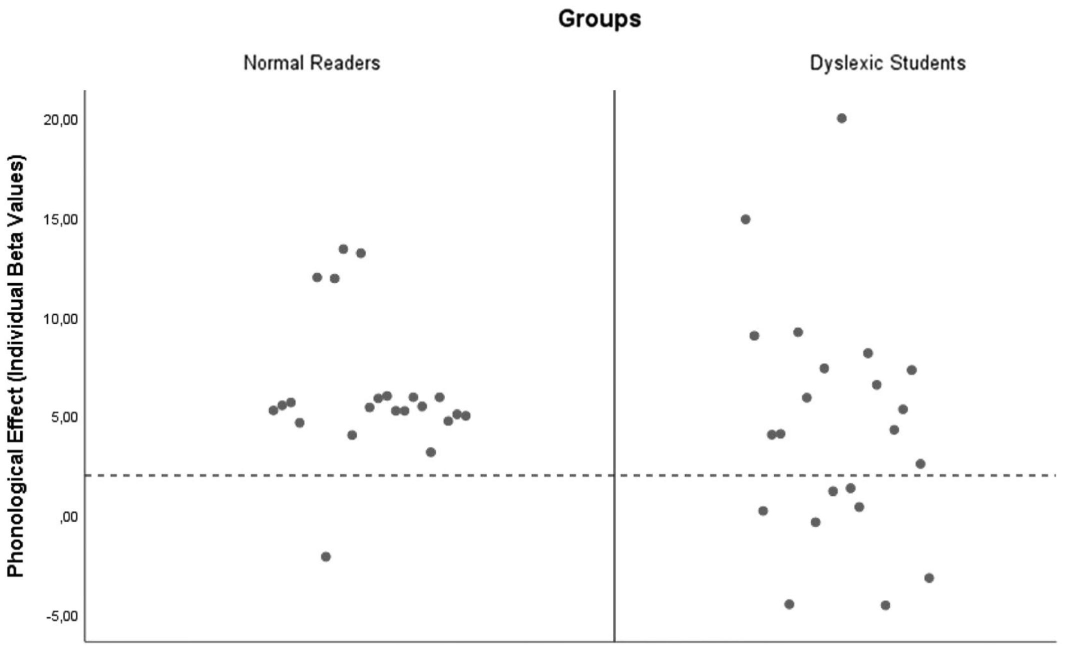

FIGURE 2 Individual betas of the phonological effect. The dashed line indicates the threshold of −1.5 SD in the normal readers

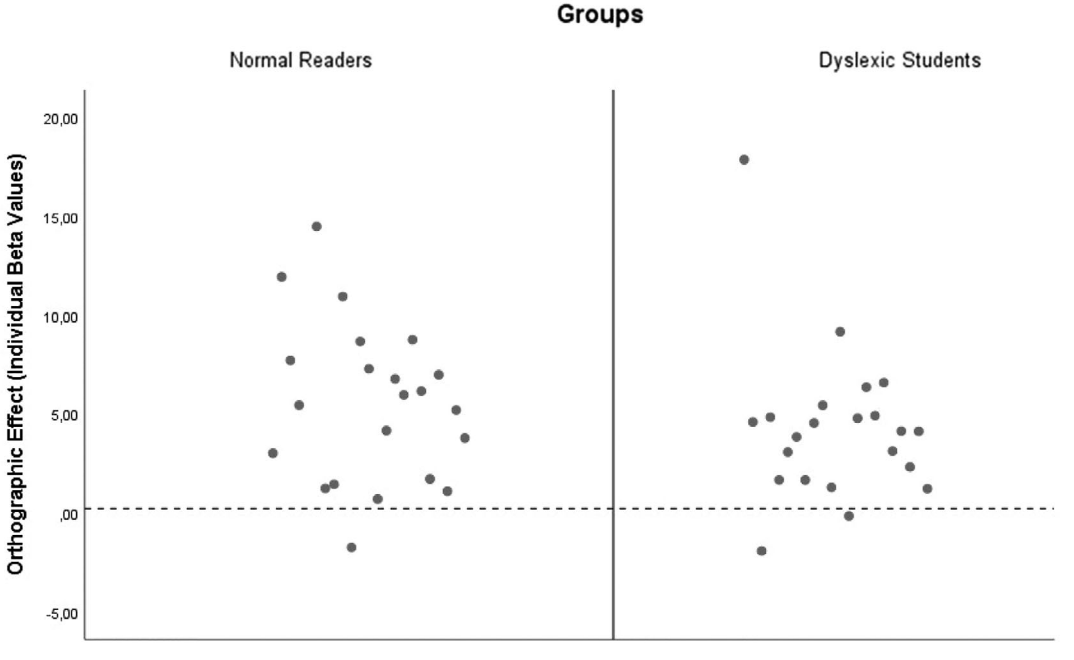

FIGURE 3 Individual betas of the orthographic effect. The dashed line indicates the threshold of −1.5 SD in the normal readers

significant predictors of performance. These results fully replicate what was observed by Chetail and Content (2014). Interestingly, the orthographic and phonological effects were significant in both groups: in typically developing readers, $\beta = -5.49$, $t = -7.44$, $p < .001$ (orthographic effect) and $\beta = 6.22$, $t = 5.73$, $p < .001$ (phonological effect), and in students with dyslexia, $\beta = -4.25$, $t = -6.39$, $p < .001$ (orthographic effect) and $\beta = 4.50$, $t = 4.61$, $p < .001$ (phonological effect). However, we found a significant interaction between the group and the phonological effect, $\beta = -2.20$, $t = -2.74$, $p = .005$, indicating that the phonological effect was greater for typically developing readers, while the interaction between the group and the orthographic effect was not significant, $\beta = 1.43$, $t = 1.80$, $p = .07$.

To assess the strength of the individual phonological and orthographic effects, we performed a regression analysis on each participant's data, and we used the beta coefficients of the resulting equation for the orthographic and the phonological effect to examine the respective influence of the orthographic and phonological structure for each participant. Individual betas are plotted in Figure 2. We observed that only one good reader obtained a negative phonological effect. This performance aside, nine of the 22 students with dyslexia (40.9%) showed a lower phonological effect than the control group. Furthermore, relative to the distribution of the betas in the control group (excluding the only negative score), eight students with dyslexia obtained a score below −1.5 SD (1.98). It is interesting to note the great heterogeneity within the group of students with dyslexia (betas from −4.55 to 19.98).

The same approach was carried out for the orthographic effect. We computed the control mean (of the individual betas) and the SD excluding the only negative score of the control group. Only two students with dyslexia obtained a score below −1.5 SD (0.23), compared with one in the control group, making these two groups similar, as suggested by the lack of any significant interaction between the group and the orthographic effect (see Figure 3).

5 | DISCUSSION

The aim of the present study was to examine to what extent adults with dyslexia are sensitive to the orthographic and phonological word structure during the earliest stages of visual word identification. For this purpose, French-speaking students diagnosed with dyslexia in childhood and students without learning disabilities performed a length estimation task. They had to estimate the physical length of words visually presented (Chetail & Content, 2014). The words differed in the number of syllables and the number of vowel letter clusters. In the control words, the number of syllables was congruent with the number of vowel groups, whereas the hiatus words comprised fewer orthographic units than syllables. On the one hand, the comparison of control and hiatus words made it possible to assess the influence of the orthographic structure. On the other hand, the impact of the phonological structure was assessed by comparing bi- and tri-syllabic words.

First, as expected, the pattern of results obtained in typically developing readers replicated the one obtained by Chetail and Content (2014). We found both a phonological effect and an orthographic effect. Both the number of syllables and the number of vowel cluster units biased length estimates when the length of the words was strictly controlled for. Given that the task does not require word identification or access to phonology, this suggests that early stages of word processing are impacted by the orthographic and phonological structure of words, and that these orthographic and phonological representations are automatically elicited.

In students with dyslexia, we also observed an orthographic and a phonological effect in the length estimation task. These data indicate that CV units and phonological syllables are both parsing units used by students with dyslexia in reading. However, a significant interaction was found between the phonological factor and the group, showing that students with dyslexia are less sensitive to the phonological structure. The interaction between the group and the orthographic factor was also close to the significance threshold ($p = .07$), but the descriptive analysis of the individual effects confirmed that students with dyslexia were less impacted by the phonological structure of words, whereas the two groups were very similar regarding the orthographic effect.

First, regarding the phonological effect, the group analysis indicated a weaker sensitivity to phonological structure in students with dyslexia, as predicted. This is in line with the findings of Doignon-Camus et al. (2013) in children with dyslexia, indicating an impaired access to phonological syllables from letters. However, it should be noted that the pattern of the results is heterogeneous, and the analysis of individual performance provides more nuanced results than the overall trend. This is hardly surprising, as previous studies have already shown significant heterogeneity in adults with dyslexia (Erskine & Seymour, 2005; Leinonen et al., 2001; Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007), and although many group analyses emphasize a deficit in phonological processing, it is not clear what proportion of adults with dyslexia actually show deviant performance in which particular aspect of phonological processing (Schraeyen, Vanderauwera, & Vandermosten, 2020). In the present study, some students with dyslexia showed little or no impact of the phonological structure (more than 40%), but others demonstrated an equal or even greater phonological effect than typically developing readers. On the contrary, all of them obtained at least one score more than 1.5 SD below the mean of the control group in the phonological tasks (pseudoword reading, phoneme deletion, digit span and rapid automatized naming). This suggests the persistence of a deficit in phonological processes and is consistent with previous studies showing difficulties in phonological skills in adults with dyslexia (Ramus, 2003; Snowling et al., 1997). Hence, in adults with dyslexia, the presence of a phonological deficit does not necessarily entail a lack of sensitivity to syllabic structure in the present task. The absence of a phonological effect in the length estimation paradigm could stem from slower access to phonology. Indeed, some students with dyslexia might need a longer exposure duration than others to extract phonological structure.

Regarding the orthographic effect, the results suggest that the sensitivity to the orthographic structure of written words (CV pattern) is preserved in students with dyslexia. Indeed, contrary to our prediction, the orthographic effect does not differ significantly between students with and without reading impairment. In contrast, students with dyslexia had low-quality orthographic representations, as indicated by their lower performance in the word spelling task. This suggests that, despite difficulties in storing and/or retrieving orthographic representations of words, early stages of prelexical orthographic processing, in particular the extraction of orthographic structure, are efficient in students with dyslexia. The presence of an orthographic effect is consistent with the results obtained by Doignon-Camus et al. (2013) in French children with dyslexia, who reported an impaired access to phonological syllables but a preserved ability to exploit orthographic redundancy. On the contrary, our results are inconsistent with previous studies indicating impaired visuo-orthographic information processing from the early stages of letter sequences processing in adults with dyslexia (Araújo et al., 2015; Pitchford et al., 2009).

An interesting perspective for future research, which would require new groups of participants, concerns the presentation time of the items. Chetail and Content (2014) used two different exposure durations of words on the screen (100 vs. 50 ms). The orthographic bias was unaffected by exposure duration. By contrast, the phonological bias, which was present with an exposure duration of 100 ms, decreased by half and failed to reach significance with an exposure duration of 50 ms. These results led the authors to conclude that the CV structure is extracted during the early phases of letter string processing, and that this process occurs before access to phonological information. We used a 100 ms exposure time to assess both orthographic and phonological biases in students with dyslexia, and in follow-up studies, it would be interesting to conduct the same task with a 50 ms exposure duration (to test if the orthographic effect remains significant) or a longer duration (to test if the phonological effect increases). This could be a way to test the hypothesis that the phonological deficit involved in dyslexia is a deficit of access to phonological representations and not a deficit due to poor phonological representations (Ramus & Szenkovits, 2008).

It is important to consider the fact that this study, focusing on the phonological structure determined by the number of syllables of the words, was conducted among French-speaking adults. The "syllabic bridge hypothesis" (Doignon-Camus & Zagar, 2014) suggests that French-speaking pre-readers learn print-to-sound associations by syllable-size units. While the syllable seems to be an important reading unit in French, which is often considered to be a syllable-timed language, cross-language differences have been found in the processing of syllables (Duncan, Colé, Seymour, & Magnan, 2006). One limitation of the present study is, therefore, that the results cannot be generalized to other languages, for which other units could play a predominant role (e.g., onset-rime units). Furthermore, our sample of students, diagnosed with developmental dyslexia in childhood, came from a high-achieving dyslexic population. Their reading achievements are good enough for them to continue on to higher education. Hence, it is likely that their reading impairments are milder compared with the dyslexic population as a whole (Gallagher, Laxon, Armstrong, & Frith, 1996). Therefore, the present findings cannot be generalized to the whole population of adults with dyslexia.

Finally, it should be noted that research on parsing cues in reading has an indirect but interesting clinical impact. Indeed, a better understanding of failing or preserved processes in dyslexia may point to treatment strategies that could be useful to improve reading. Weaker sensitivity to phonological structure in visual word recognition could be helped by strategies such as providing visual cues to facilitate syllable parsing or grapho-syllabic conversion training. For example, Gallet, Viriot-Goeldel, and Leclercq (2019) proposed a remediation program for French students with reading difficulties in elementary school. This program included training based on grapho-syllabic conversion (focusing on syllable units) and demonstrated beneficial effects on struggling readers. According to these authors, grapho-syllabic conversion training is a promising way to improve phonological decoding (see also Ecalle, Magnan, and Calmus (2009). This is in line with the research of Doignon-Camus and Zagar (2014, 2006), which suggests that the syllable could be a pertinent unit in the learning-to-read process in French.

6 | CONCLUSION

The present study examined the orthographic and phonological structure effects on identification of written words in French higher-education students. Our results closely replicate those obtained by Chetail and Content (2014): we found a phonological effect and an orthographic effect in typically developing readers. In students with dyslexia, we observed lower sensitivity to the phonological structure of words, which is consistent with evidence of impaired phonological processing. However, the lack of sensitivity to phonological structure was not present in all students with dyslexia, reflecting the typical heterogeneity in such samples, and further research is needed to better understand the complexity of their profiles. In contrast, the orthographic effect did not differ significantly between students with and without reading impairment, suggesting that the sensitivity to the orthographic structure of written words is preserved in students with dyslexia.

DATA AVAILABILITY STATEMENT

All the materials, raw data, and scripts for the analyses are available on the Open Science Framework: https://osf.io/bgz2h/.

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How to cite this article: Collette, E., Content, A., Schelstraete, M.-A., & Chetail, F. (2021). The extraction of orthographic and phonological structure of printed words in adults with dyslexia. *Dyslexia*, 1–16. https://doi.org/10.1002/dys.1700